Synthetic Aperture Sonar Beam Forming in the Presence of Internal Waves

Larry V. Johnson
Joshua Eisenberg
Jesse Goldberg

Arete' Associates
P.O. Box 6024
Sherman Oaks, CA 91414
phone:(818) 501-2880fax:(818) 501-2905   email: ljohnson@arete.com
Award #: N00014-99-C-0247
http://wavelet.apl.washington.edu/CMO

LONG-TERM GOAL

The long-term goal of our research is to incorporate environmental estimation and compensation methods into the synthetic aperture sonar (SAS) image formation process. Specifically, our goal is to mitigate shallow water environmental effects that result in degradation of image resolution through space/time variations in the sound speed field, e.g., internal waves, turbulence, bathymetry.

OBJECTIVES

The current focus of our research is to develop an algorithm to compensate for the effects of linear internal waves during the formation of a synthetic aperture in a shallow water environment. Internal waves impact the propagation of the acoustic signal and consequently the phase by changing the space time structure of the sound speed field. Our intent is to model this phase change due to internal waves, with the challenge of developing a methodology to remove this internal wave induced phase variation as a part of the formation of the synthetic aperture.

Our research objectives are consistent with the goals of the SAS PRIMER experiment, which is affiliated with the overall Coastal and Mixing Optics Experiment conducted during 1996, [1]. The experimental emphasis is on high frequency acoustic propagation through shallow water internal waves, characterization of linear and nonlinear shallow water internal waves, and SAS beam formation.

APPROACH

The specific approach we are taking is first to construct a simulation of the phase history of a point target in the presence of an internal wave field, with initial emphasis on linear internal waves. The model is a combination of ray theory, the method of Gaussian beams [2], and generating a realization of a sound speed field perturbed by linear internal waves through which the rays propagate. The primary inputs are sound speed and Brunt-Vaisala (BV) frequency profiles derived from in-situ measurements obtained at the PRIMER SAS experimental site [3] [4].

We use the synthetic phase history as an aid in developing a simple forward model that comprehends the internal wave phase perturbation. We then embed the forward model in a beam formation

algorithm. The forward model consists of a simplified Gaussian beam ray trace formulation with a depth dependent sound speed profile as the zeroth order unperturbed propagation model, and a Rytov approximation to include the internal wave effects as a phase perturbation to the zeroth order model. As an initial test we will use time of arrival series, sensor navigation and angle of arrival series along the synthetic aperture as the synthetic data from which the forward model parameters are estimated.

WORK COMPLETED

Utilization of empirical orthogonal functions [5] (EOFs) as a means of estimating a zeroth order depth-dependent sound velocity profile (SVP) based on multi-path time-of-arrival and angle-of-arrival data in the presence of internal waves.

Development of a forward model of an internal wave field that partially compensates for internal wave induced phase perturbations in synthetic multi-path time-of-arrival data.

Development of an in-house SAS processor applied to data we received from CSS as a benchmark, as well as to our own synthetically generated stave data. We are using this processor to assess the theoretical impact of internal waves and refraction on SAS beam formation.

RESULTS

We were supplied with a database of depth-dependent sound velocity profiles from the SAS PRIMER experiment. Using selected SVPs, we then synthesized time-of-arrival and angle-of-arrival data for specific acoustic projector / receiver / target geometries in the presence of internal waves with an eigenray search algorithm. Our results indicate that the construction of a set of empirical orthogonal functions is a more efficient and stable method of representing a zeroth order SVP than using a polynomial depth-dependent SVP. With the EOF method, we were able to converge on a zeroth order SVP for synthetic data with four eigenray paths across a synthetic aperture; with the polynomial representation, we were only able to construct a zeroth order SVP for synthetic data with up to two eigenray paths. Shown in Fig. 1a is an example of the implementation of empirical orthogonal functions used to estimate a zeroth order depth-dependent SVP based on four synthetic time-of-arrival and angle-of-arrival series in the presence of simulated internal waves. Shown in Fig. 1b is a one-ping sample of the corresponding synthetic data eigenrays and our estimates of those eigenrays based on the zeroth order SVP from Fig. 1a. Although the estimated eigenray paths do not match those of the synthetic data perfectly, they provide reasonable estimates for the four time-of-arrival series, upon which an internal wave induced phase perturbation can be added.

20kHz synthetic data were generated at a 1km standoff range that contained two eigenrays across a 375m aperture. Associated with each eigenray series is an internal wave induced residual phase series (defined as the internal wave time-of-arrival series minus the time-of-arrival series without internal waves, converted to degrees). We were able to estimate these residual phase series with a zeroth order model, and partially compensate for both of the residual phase series simultaneously with a single realization of a shallow water Garrett-Munk-like internal wave spectrum. This is illustrated in Fig. 2. This result is an improvement over previously reported results because we are now able to include more than one time-of-arrival series in the internal wave compensation algorithm.

Fig. 3 is an example of 20kHz CW pulse multi-path synthetic stave data generated by implementing an eigenray search algorithm in combination with the method of Gaussian Beams. Each eigenray has

associated with it a time of arrival and a pressure amplitude. For the example in Fig. 3, we simulated a 70m depth water column with an SVP obtained from the PRIMER experiment. The acoustic projecter / receiver were at a 20m depth, while the target was at the bottom (70m). Eigenrays were collected over a 200m horizontal aperture with 5cm spacing between pings and a 500m standoff range at closest approach. This would ideally result in 10cm azimuthal resolution (a point response function with a 3dB width of 10cm).

We implemented the Wavenumber Algorithm [6] to develop a SAS processor. Fig. 4 illustrates our preliminary assessment of the effects of vertical (range-independent) refraction, position- and time-dependent internal waves, ambient noise, and multi-paths on a beamformed image of the synthetic stave data described above. As illustrated in Fig. 4, the combined effects of vertically stratified refraction, internal waves, multi-paths and ambient noise severely degrade the SAS point response function.

IMPACT/APPLICATION

The development of a compensation scheme for environmental effects is important for the situations when moderately high frequency sonar is working at longer stand off ranges that require increased resolution for the detection and classification of objects lying on the bottom. We have examined linear internal waves as one environmental source of resolution loss in the formation of a synthetic aperture beam. Continuing development of a compensation scheme can lead to improved beam formation algorithms with increased resolutions and with environmentally adaptive capabilities to estimate and mitigate the defocusing effects associated with internal waves, refraction and multi-path returns.

TRANSITIONS

There are currently no actions being taken to transition the results of this work to other projects

RELATED PROJECTS

1) The shallow water internal wave characterization being done by Murray Levine at OSU has provided the initial sound speed and BV profiles used in the simulations along with the initial characterization of the linear internal wave shallow water spectrum

2) The analysis of SAS PRIMER acoustic data by UW/APL to determine the impact of internal waves on beam formation across an array of hydrophones on a tower, and on acoustic wave propagation

3) Analysis of data obtained from a tow fish during the SAS PRIMER experiment by NRL Stennis with the intent of studying synthetic aperture formation in the presence of internal waves.
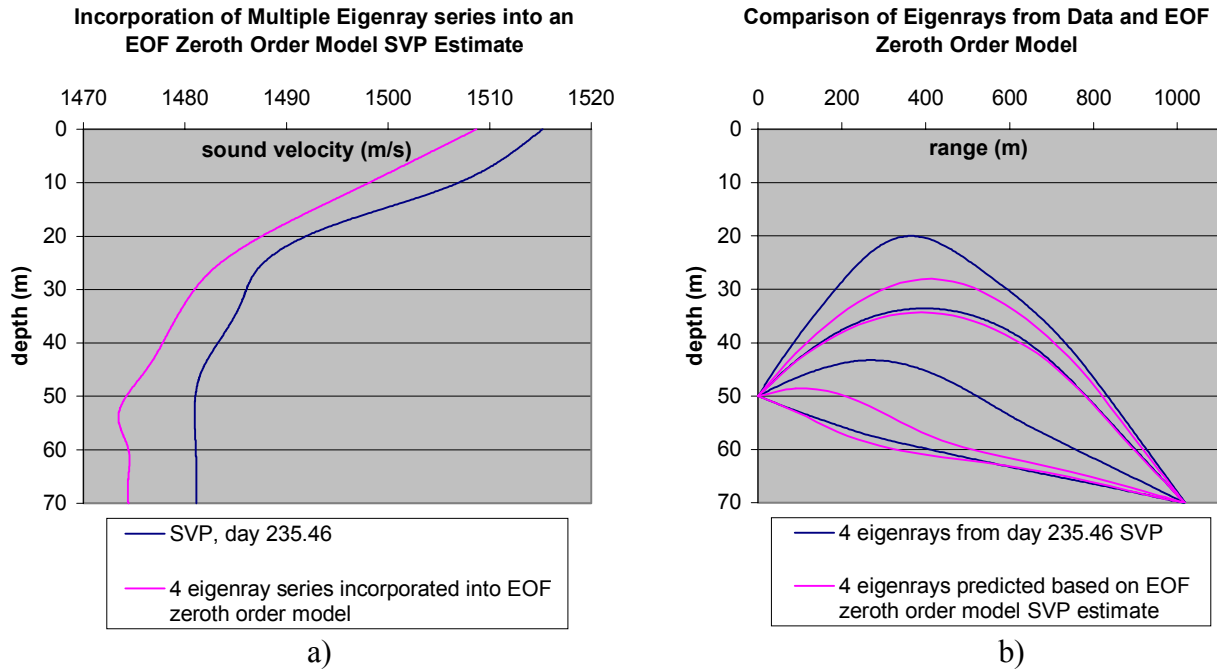
Fig. 1:
a) example of a zeroth order estimate of the PRIMER sound velocity profile (day 235.46), from simulated four multi-path time of arrival data series in an internal wave field with 5 vertical modes. b) one example ping of four simulated data eigenrays and four eigenrays predicted based on the zeroth order sound velocity profile in Fig. 1a).
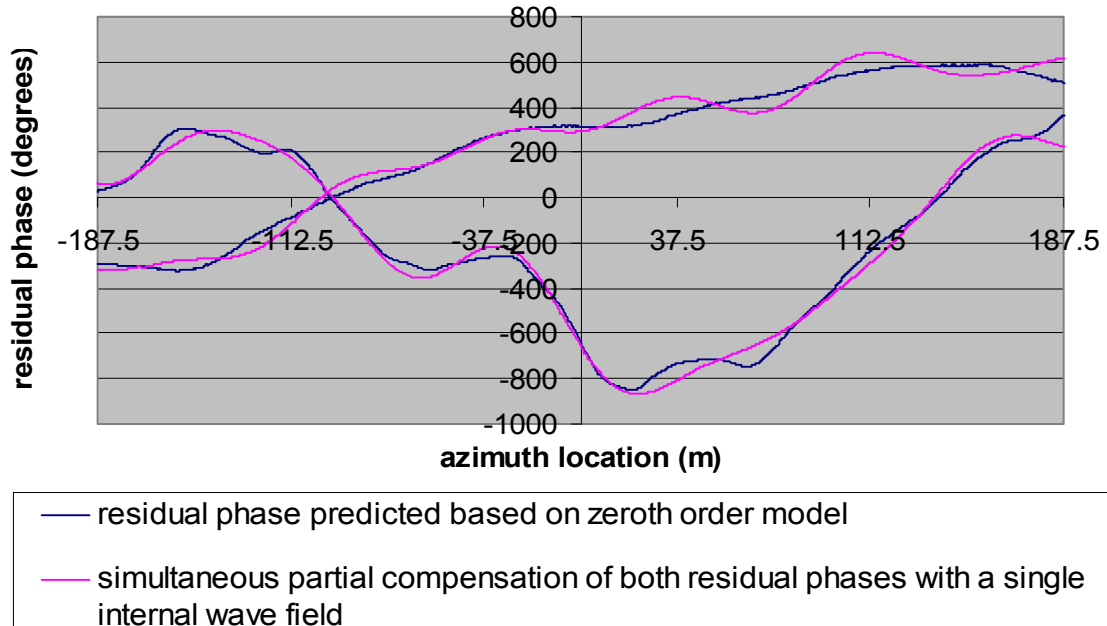

Fig. 2:
In blue: predicted residual phases due to internal waves, from simulated two-path time-of-arrival and angle-of-arrival data series in an internal wave field with 5 vertical modes. In pink: A one vertical mode Garrett-Munk-like internal wave field realization that simultaneously partially compensates for both residual phase histories.
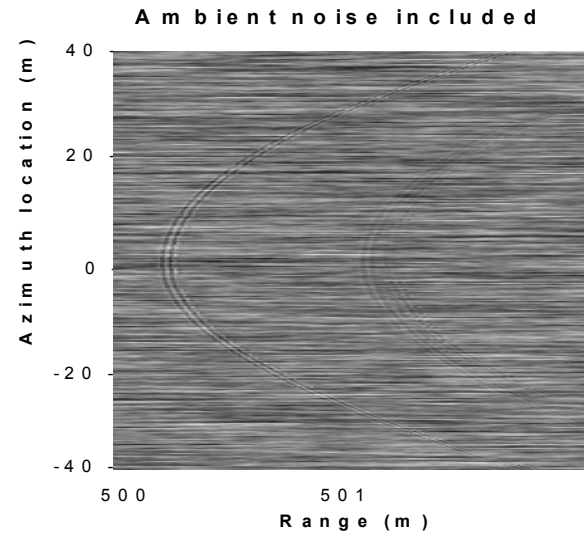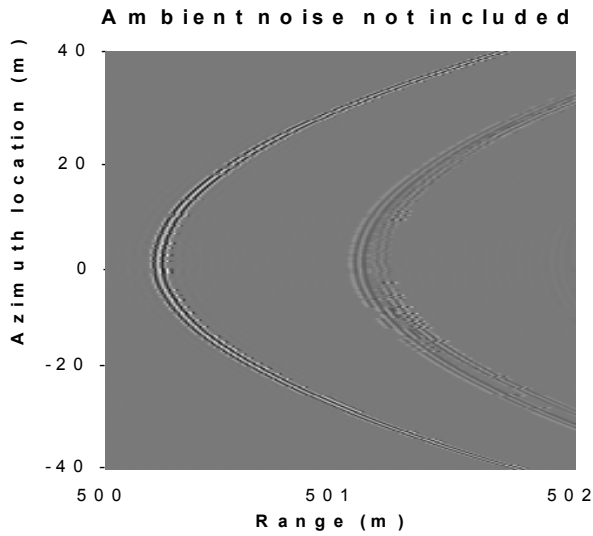
Fig. 3:
An example of simulated multi-path eigenray stave data in the presence of internal waves, with and without ambient noise. Simulated water column was 70m deep, SVP from day 235.46, receiver / projector depth = 20m, target depth = 70m. Simulated internal wave field contains 5 vertical modes.
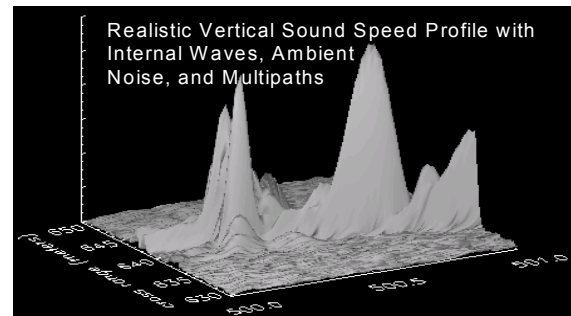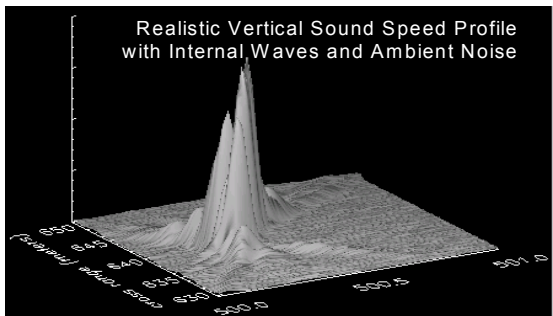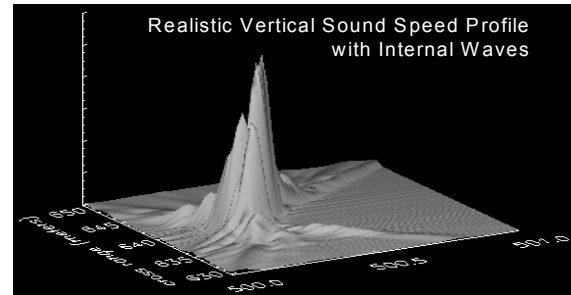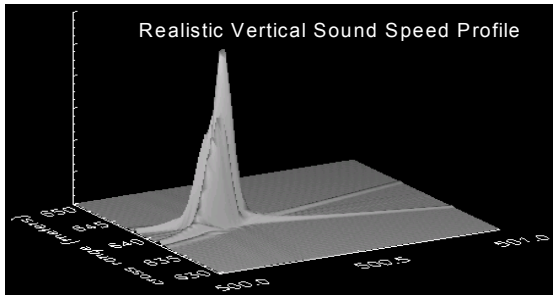

Fig. 4:
Illustration of the degradation in resolution of the SAS point response function with the introduction of the following environmental parameters: vertical refraction, internal waves, ambient noise, multi-paths.

REFERENCES

1   a) F.S. Henyey, J.M. Grochocinski, S.A. Reynolds, D.Rouseff, "Pre experiment modeling:Effects of internal waves and turbulence on a synthetic aperture sonar (SAS)," Applied Physics laboratory, Seattle, WA, Rep.

        b)F.S. Henyey, D. Rouseff, J.M. Grochocinski, S.A. Reynolds, K.L. Williams, T.E. Ewart, "Effects of Internal Waves and Turbulence on a Horizontal Aperture Sonar," IEEE J. Oceanic Eng., Vol.22, No.2, April 1997

2   M.B. Porter, H.P. Bucker, "Gaussian beam tracing for computing ocean acoustic fields," J.Acoust.Soc.Am. 82, 1349-1359 (1987)

3   Private communications with Murray Levine

4   T. Boyd, M.D. Levine, S.R. Gard,"Mooring Observations from the Mid-Atlantic Bight July-September 1996," Oregon State University Report, Data Report 164, Reference 97-2

5   A. Tolstoy, O. Diachok and L.N. Frazer, "Acoustic Tomography Via Matched Field Processing," J. Acoust. Soc. Am. 89 (3), pp. 1119-1127, Mar. 1991.

6   Peter T. Gough and David W. Hawkins, "Unified Framework for Modern Synthetic Aperture Imaging Algorithms," The International Journal of Imaging Systems and Technology, vol. 8, no. 4, pp. 343-358, (1997).